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1 **The effect of water depth on limb kinematics of the domestic dog (*Canis lupus***
2 ***familiaris*) during underwater treadmill exercise**

3 The Effect of Water Depth on Canine Underwater Treadmill Exercise

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Abstract

Canine hydrotherapy is an increasingly popular modality for the rehabilitation of dogs; however, little evidence exists to support the use of current hydrotherapy protocols. Before data can be meaningfully collected from pathological animals, biomechanical data for healthy animals is required. Kinematic analysis was utilised to observe the effect of increasing water depth on the stride parameters (including duty factor) of dogs exercising on a canine hydrotherapy treadmill. During two sessions, eight clinically sound adult dogs walked on the underwater treadmill at four different water depths (dry, mid-tarsal, between the lateral malleolus and the lateral epicondyle, and between the lateral epicondyle and greater trochanter). Reflective kinematic markers were placed onto anatomical limb landmarks and a video camera was used to record foot contacts at 60Hz. Data were digitised using video analysis software and stride length, stride frequency and duty factor were subsequently calculated. Data were analysed using the Friedman Test and Wilcoxon post hoc pairwise tests to identify differences between conditions. There was a significant effect of water depth on duty factor ($p<0.0005$). Hind limb duty factor differed significantly from fore limb duty factor ($p<0.0005$), except at the depth between the lateral malleolus and the lateral epicondyle where no significant difference was observed. There was a significant effect of water depth on both stride frequency ($p<0.0005$) and stride length ($p<0.0005$). In summary, water depth has a significant impact on the stride parameters of dogs exercising on the canine hydrotherapy treadmill and as such is an important consideration when designing underwater treadmill based rehabilitation programs.

Keywords: Duty Factor, Hydrotherapy, Dogs, Rehabilitation

Introduction

Hydrotherapy is a valuable tool for the physiotherapy and rehabilitation of dogs and horses (King *et al.*, 2013; Prankel, 2008; Scott *et al.*, 2010). Underwater treadmill (UWT) therapy is increasing in popularity as a canine rehabilitation tool and has been previously used in the promotion of health, prevention of injuries, effective treatment, rehabilitation and performance enhancement (Houlding, 2011). An increased understanding of the effects of the UWT on animal locomotion is highly beneficial in designing more effective treatment and rehabilitation programs (Houlding, 2011). There is a need for evidence informed practice in therapeutic regimens which is currently lacking in the field of canine hydrotherapy.

Movement through water results in several changes to quadrupedal locomotion. Buoyancy allows a reduction in impact and weight bearing on the limbs during exercise resulting in a decreased risk of damage to injured and healing limbs (Kilding *et al.*, 2007; King *et al.*, 2013; Levine *et al.*, 2010; Owen, 2006). Hydrostatic pressure, caused by submersion assists extracellular fluid in returning to the central body cavities which is beneficial for the treatment of swollen joints and oedema in the lower limbs (King *et al.*, 2013; Owen, 2006; Prankel, 2008; Saunders, 2007; Wilcock *et al.*, 2006). Exercising in water also increases the level of resistance to the movement of the limb when compared to exercise out of water (in air), thus increasing muscle work and energy expenditure (King *et al.*, 2013; Owen, 2006; Prankel, 2008). These properties make both swimming and UWT therapy increasingly popular choices for the exercise and rehabilitation of dogs.

There are a number of different types of canine hydrotherapy including swimming and UWT therapy each of which have their own benefits (Formenton, 2011; Houlding, 2011; King *et al.*, 2013; Owen, 2006; Prankel, 2008; Saunders, 2007; Waining *et al.*, 2011). Potential applications for hydrotherapy and in particular UWT include increasing joint mobility,

reducing lameness, increasing cardiovascular fitness and treating dogs for conditions such as arthritis, postoperative recovery, fractures, neurological impairments, tendonitis, sprains and strains (Formenton, 2011; King *et al.*, 2013; Owen, 2006; Saunders, 2007; Scott *et al.*, 2010). UWT therapy can also prove advantageous over swimming as variables such as water depth and treadmill speed can be altered allowing for flexibility in the design of treatment protocols (Owen, 2006; Prankel, 2008; Saunders, 2007; Scott *et al.*, 2010; Wilcock *et al.*, 2006). Furthermore, UWT therapy enables restricted straight line locomotion which is difficult to achieve during swimming which usually necessitates a certain degree of manoeuvring.

The Veterinary Surgery (Exemptions) Order (1962) allows the treatment of animals by a physiotherapist acting under veterinary referral. There are, however, a number of factors that can have an impact on the efficacy of underwater treadmill therapy including the skill of the therapist, the severity of the condition and the timing of veterinary referral (Houlding, 2011; Prankel, 2008). It has been stated that the use of inappropriate techniques can have a detrimental impact on pre-existing injuries and conditions (Waining *et al.*, 2011). In addition, suitable water management techniques are required to ensure the safety of both practitioner and client (Houlding, 2011).

Despite the potential variability of the outcome, research into the effects of UWT based therapy is currently limited (Houlding, 2011; Prankel, 2008; Scott *et al.*, 2010; Waining *et al.*, 2011). Research investigating the effect of hydrotherapy on range of motion (ROM) in dogs is minimal (Marsolais *et al.*, 2003). One study, Monk *et al.* (2006) concluded that hydrotherapy UWT exercise resulted in a greater range of movement in the stifle joint and increased thigh circumference over a 6 week period compared to controlled walking in cranial cruciate ligament deficient dogs after a tibial plateau osteotomy, and would represent an increased chance of dogs returning to full locomotor function compared to walking alone (Monk *et al.*, 2006). Equine studies have demonstrated that walking in deeper water (carpal and ulna height) on the UWT decreased stride frequency and increased stride length, whilst it has been suggested that the UWT treadmill and swimming may be effective treatments for equine osteoarthritis (King *et al.*, 2013; Scott *et al.*, 2010). However, little research has been conducted into the kinematics of healthy dogs on the UWT. Normal gait parameters (including duty factor) must be measured before the effect of UWT on the rehabilitation of pathological conditions can be accurately quantified (Clements *et al.*, 2005). Recording changes in stride frequency and stride length could provide information on how factors such as resistance and buoyancy influence gait parameters and therefore provide information for the formation of tailored, evidence-based rehabilitation programs (Scott *et al.*, 2010). An increase in stride length may facilitate an increased ROM in dogs recovering from pathologies and surgical procedures.

Understanding the kinematics and kinetics of healthy dogs walking on the UWT is essential before treatment programmes for pathological animals can be developed. Many different gait parameters can be studied including stride length, stride frequency and duty factor. Duty factor is defined as the fraction of the stride period that the limb is in contact with the ground (Biewener, 2003; Blaszczyk and Dobrzecka, 1989; Irschick and Jayne, 2000; Witte *et al.*, 2004). Duty factor changes as an animal increases its speed, mammals achieve the longer strides needed for speed by reducing duty factor (Alexander, 2003; Biewener, 2003). There is little published data on the duty factor of quadrupedal animals moving in water or the effect of water depth on duty factor. It has been suggested that the increased density and viscosity of water may affect the timing of limb movements (Ashley-Ross *et al.*, 2009). Due to the detrimental effect of drag, the velocity at which the limbs are swung through the water is decreased, which combined with a decrease in duty factor, leads to a longer absolute swing

time (Martinez, 1996). Buoyancy also acts to prolong the swing time and helps to reduce the effect of drag during aquatic locomotion (Ashley-Ross *et al.*, 2009). There are kinetic implications of duty factor, as less force is applied through the limb if relative stance time is increased (Alexander, 2003; Biewener, 2003). Therefore, if an increased water depth does decrease duty factor, as could be expected due to the effect of buoyancy, this may increase concussive forces exerted on the injured limb and therefore should be an important consideration in the selection of water depth. In addition, studies have shown underwater locomotion to be characterised by more variable gait patterns (Ashley-Ross *et al.*, 2009). This may also have clinical implications for convalescing animals, as a less controlled gait may exacerbate pre-existing conditions (Peham *et al.*, 2004). The conditions that are most commonly referred for canine hydrotherapy include cranial cruciate ligament rupture (post-surgery) and hip dysplasia (Houlding, 2011). It has been demonstrated that abnormal dynamic joint movement of cranial cruciate ligament deficient joints may result in joint degeneration, hence any change to gait induced by a treatment protocol should be carefully considered (Tashman *et al.* 2004).

The objective of this study was to quantify the effect of four water depths (dry, mid tarsal, between the lateral malleolus and the lateral epicondyle and between the lateral epicondyle and the greater trochanter) on the duty factor, stride length and stride frequency of eight healthy dogs walking on a canine hydrotherapy treadmill. It was firstly hypothesised that increasing the water depth within a hydrotherapy treadmill would increase the stride frequency (Hz) and decrease the stride length (m) of dogs walking underwater as documented in other terrestrial quadrupeds (Scott *et al.*, 2010). Secondly, it was hypothesised that due to the properties of water, canine underwater locomotion would be characterised by reduced duty factors at increased depths.

Materials and Methods

The study took place at the Cotswold Dog Spa at Hartpury College, Gloucester, Gloucestershire, United Kingdom. The study was performed in line with the Hartpury University Centre institutional ethical guidelines.

Animals

Eight clinically sound adult dogs of mean age 3.31 ± 1.39 years were included in the study. All dogs were free from any musculoskeletal abnormalities and were examined by a veterinarian prior to participation in the study. Owners were required to complete a consent form and were provided with an information sheet detailing the experimental protocol. Dogs were of various breeds with a mean body mass 28.79 ± 8.79 kg, mean forelimb length 57.88 ± 8.75 cm and mean hind limb length 53.88 ± 7.24 cm. Dogs were acclimatised to the four different water depths of the treadmill in three sessions held prior to commencement of the study (Monk *et al.*, 2006). This process of habituation ensured repeatability of gait parameters across trials.

Marker Placement

Two-dimensional circular reflective adhesive markers (radius 7mm) were produced from silver duct tape and placed on to two pre-defined bony anatomical landmarks on the left side of the dog by the same investigator. This took place whilst the dog was standing squarely with equal weight distribution on all four limbs. This method of marker placement is consistent with previous kinematic studies (Clayton and Schamhardt, 2001; Marsolais *et al.*, 2003). Markers were placed onto the distal lateral aspect of the metacarpus and fifth metatarsal.

Underwater Treadmill

A Westcoast Hydrotherapy treadmill (Westcoast Hydrotherapy, Norfolk, United Kingdom) with internal dimensions of 1.82m (length) x 0.68m (width) x 0.90m (height) was used for the study. To facilitate the recording of stride length, 10cm intervals were indicated and calibrated along the horizontal plane of the treadmill window. Water temperature, room temperature and water pH were measured before each dog performed their trials to monitor for any fluctuation that could affect the data recorded. The water treadmill glass was cleaned between each subject to ensure optimum visibility and marker detection.

Kinematic Analysis

Limb movements were recorded with a digital video camera (Sony® Model HDR-CX330E, 9.2 mega pixels; Sony, Weybridge, UK) interlaced at 60Hz. The camera was used to capture the foot contacts of the forelimb and hindlimb within the treadmill. The video camera was mounted on a tripod at 1.23m high and 0.26m from the sagittal plane of the underwater treadmill.

Experimental Design

On arrival at the hydrotherapy centre, each dog had its collar and lead removed and was fitted with a Webmaster safety harness (Ruffwear, County Durham, UK). The dogs were then guided onto the treadmill by a registered hydrotherapist (National Association of Registered Hydrotherapists). Each dog was also fitted with a Heart Rate Monitor S81Oi watch (Polar

Elector Ltd, Warwick, UK) that was used to monitor the return to a resting heart rate between trials and thus ensure that subjects were not unduly exerted.

All subjects completed two sessions in a randomised cross over design at the following water depths: dry, mid tarsal, between the lateral malleolus and the lateral epicondyle, and between the lateral epicondyle and the greater trochanter. Each of the water depths were controlled specific to the leg length of the subject but were at the same anatomical point of each dog, for example, mid tarsal (Figure 1). The sessions consisted of the dogs exercising at each of the four water depths for 150 seconds with a minimum 10 minute break between trials. Water heights were recorded for each dog to ensure consistency across the two repeats. For each individual, the treadmill speed was set at a comfortable walking velocity determined by the canine hydrotherapist during the acclimatisation sessions. This ensured the dogs did not undergo excessive exertion which allowed the results to be more applicable to general hydrotherapy practice.

Figure 1. Schematic of the canine hydrotherapy treadmill and the different water depths.

Data Analysis

Video recordings were analysed using motion capture software (Dartfish Analyser Software, Version 7.0, Fribourg, Switzerland). Duty factor was calculated from measurements of the stride time (s) and the stance time (s), using 150 seconds of video data. Ten randomly selected consecutive strides from the middle of the data collection period were analysed from each depth (Mendez-Angulo *et al.*, 2013). The mean duty factor (stance time/stride time) of the hind and forelimb for each speed and depth were then calculated in Microsoft Excel (version 14.0.7, Microsoft Office, Microsoft Corp, Redmond, US).

Mean stride length (m) and stride frequency (Hz) were calculated for each depth using the stride time (s) and treadmill markings. Stride length was defined as the distance between two successive footfalls of the same limb, recorded at toe on. A total of 80 strides were recorded for each subject and taken forward for statistical analysis. This included 10 strides for each dog, four conditions and two repeats of each condition.

Statistical Analysis

All statistical analyses were performed in R version 3.2.0; packages stats and pgirmess (R Core Team, Vienna, Austria). The Kolmogorov-Smirnov test was used to determine whether the data were normally distributed. Data were non-parametric so a Friedman Test was used to determine the effect of water depth on the kinematic parameters recorded (stride length, stride frequency, duty factor, stance time and swing time). As significant differences were identified for all kinematic parameters, post hoc tests were applied. Pairwise Wilcoxon rank sum tests, with the Bonferroni adjustment were applied such that the criterion of significance ($p < 0.05$) was divided by the number of comparisons (6). Therefore, a new criterion of significance ($p < 0.0083$) was applied to avoid spurious positive results (Field, 2013). Pairwise comparisons were also used to identify differences between forelimb and hindlimb duty factor, stance and swing time. Wilcoxon rank sum tests were used to test for differences between forelimb and hindlimb duty factor at each depth.

Results

All dogs completed the desired protocol and hence 64 complete trials were included in the analysis. This included the eight dogs completing four conditions, each of which was performed twice by each dog.

212 *Duty Factor*

213 There was a significant effect of water depth on duty factor of both the forelimb ($p<0.0005$)
 214 and the hindlimb ($p<0.0005$) of the dogs. Pairwise post hoc testing (Table 1) revealed
 215 significant differences in forelimb duty factor between all water depths ($p<0.0005$). There
 216 was a significant difference in hindlimb duty factor ($p<0.0005$) at all depths apart from
 217 between the lateral malleolus and lateral epicondyle (3) to between the lateral epicondyle and
 218 the greater trochanter (4) ($p = 1.00$).

219 Duty factor was significantly higher in the hindlimb ($p<0.0005$), with differences identified at
 220 all depths apart from the depth between the lateral malleolus and the lateral epicondyle (3)
 221 where no significant difference ($p=0.052$) between limbs was observed (Figure 2).

222 Table 1. Post hoc comparison of stride parameters at each water depth¹

Depth			1-2	1-3	1-4	2-3	2-4	3-4
Duty Factor	FL	W	19668	22028	23502	16662	19710	17120
		p	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*
		P adj.	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*
	HL	W	19863	22298	22863	17205	16981	12034
		p	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	0.36
		P adj.	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	1.00
Stride Length		W	10959	7549	5266	8824	6174	9665
		p	0.02489	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*
		P adj.	0.14931	<0.0005*	<0.0005*	<0.0005*	<0.0005*	0.00082*
Stride Frequency		W	87090	95734	99020	71872	85596	70500
		p	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*
		P adj.	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*
Stance Time	FL	W	8683	7112	7879	11141	11284	12808
		p	<0.0005*	<0.0005*	<0.0005*	0.04	0.06	0.99
		P adj.	<0.0005*	<0.0005*	<0.0005*	0.27	0.40	1.00
	HL	W	9428	9199	5779	12566	8918	9097
		p	<0.0005*	<0.0005*	<0.0005*	0.78	<0.0005*	<0.0005*
		P adj.	<0.0005*	<0.0005*	<0.0005*	1.00	<0.0005*	<0.0005*
Swing Time	FL	W	2555	756	306	5688	2833	6170
		P	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*
		P adj.	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*
	HL	W	1434	751	143	5754	3273	10551
		p	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	0.0064*
		P adj.	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	0.038*

	W	15402	6598	3446	30024	16877	32821
Stride Time	P	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*
	P adj.	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*	<0.0005*

¹Results of all post hoc tests for all stride parameters, including forelimb (FL) and hindlimb (HL) where appropriate. Adjusted and non-adjusted p values are shown for all pairwise Wilcoxon rank sum tests. *p < 0.0083 is significant and p adj. < 0.05 is significant. Actual p values are shown, apart from for p < 0.0005, which are not reported. W = Wilcoxon test statistic. Water depths are, 1 = dry, 2 = mid-tarsal, 3 = between the lateral malleolus and the lateral epicondyle, 4 = between the lateral epicondyle and the greater trochanter.

Figure 2. Duty factor of all dogs at four different water depths

Stride Length

There was a significant effect ($p < 0.0005$) of water depth on stride length (m). Pairwise post hoc testing (Table 1) revealed significant differences in stride length ($p < 0.001$) between all water depths, apart from between dry (1) and mid-tarsal (2) ($p = 0.15$) (Figure 3).

Figure 3. Stride length (m) at four water depths

Stride Frequency

There was a significant effect ($p < 0.0005$) of water depth on stride frequency. Pairwise post hoc testing (Table 1) revealed significant differences ($p < 0.0005$) in stride frequency between all water depths (Figure 4).

Figure 4. Stride frequency (Hz) at four water depths

Stride Time, Stance Time and Swing Time

There was a significant effect ($p < 0.0005$) of water depth on stride time. Pairwise post hoc testing (Table 1) revealed significant differences ($p < 0.0005$) in stride time between all water depths (Figure 4). There was a significant effect of water depth on forelimb stance time (s) ($p < 0.0005$). Post hoc testing (Table 1) identified significant differences ($p < 0.0005$) in forelimb stance time between dry (1) and mid-tarsal (2), between dry (1) and the lateral malleolus to the lateral epicondyle (3) and between dry (1) and the lateral epicondyle to the greater trochanter (4). There was no significant difference between mid-tarsal (2) and between the lateral malleolus and the lateral epicondyle (3) ($p = 0.27$), between mid-tarsal (2) and between the lateral epicondyle and the greater trochanter (4) ($p = 0.40$) and between the lateral malleolus and the lateral epicondyle (3) and between the lateral epicondyle and the greater trochanter (4) ($p = 1.00$). There was a significant effect of water depth on hindlimb stance time (s) ($p < 0.0005$). Post hoc testing (Table 1) identified significant differences ($p < 0.0005$) between all depths ($p < 0.0005$) apart from between mid-tarsal (2) and between the lateral malleolus and the lateral epicondyle (3) ($p = 1.00$).

There was a significant effect of water depth on forelimb swing time (s) ($p < 0.0005$). Post hoc testing (Table 1) identified significant differences between all depths ($p < 0.0005$). There was a significant effect of water depth on hindlimb swing time (s) ($p < 0.0005$). Post hoc testing (Table 1) identified significant differences between all depths ($p < 0.05$).

Figure 5. Stance and Swing Time (s) at four water depths

Discussion

Duty factor

It was observed in this study that duty factor was affected by changing the depth of the UWT. This alteration in gait could be caused by the dog heightening the flight arc in order to decrease the amount of resistance caused by an increased depth of water in the sagittal plane (Ashley-Ross *et al.*, 2009; Scott *et al.*, 2010). Consequently, the swing phase would increase and the duty factor would decrease. Dogs may alter their flight arc when walking in water due to the need to lift the limb through and above the water. This may be particularly pertinent if their stride length and frequency is constrained by speed. Biomechanical constraints to step angle may also prevent dogs from adapting to walking in water by further modifying their stance time (Usherwood, 2005). Walking in deeper water has been shown to alter body posture in horses exercising on the UWT (Nankervis *et al.* 2015). Changes in body posture were not recorded in this study but these data would help to further elucidate the adaptation of dogs to walking in water.

With increasing water depth, more of the body is supported through buoyancy, effectively reducing the weight of the animal (King *et al.*, 2013; Levine *et al.*, 2010; Owen, 2006; Prankel, 2008; Saunders, 2007). In previous studies conducted on the newt and the salamander, it was found that duty factor decreased in water compared to terrestrial locomotion as less support was needed due to the effect of buoyancy (Ashley-Ross *et al.*, 2009; Deban and Schilling, 2009). Conversely, salamanders adopt a more sprawled posture than dogs (Ashley-Ross *et al.*, 2009) and therefore this finding may lack applicability to canine locomotion. Due to the increase in resistance with increasing water depth, dogs need to increase their energy expenditure to maintain the same speed, which may have implications for animals requiring weight loss (King *et al.*, 2013; Owen, 2006; Prankel, 2008; Scott *et al.*, 2010; Wainig *et al.*, 2011).

There was no significant difference between duty factor of the forelimb and hindlimb when the water was between the lateral malleolus and lateral epicondyle (depth three), however, hind limb duty factor was higher than forelimb duty factor at the other three water depths. Other studies observing the difference in duty factor between the forelimb and hindlimb of dogs found that the mean forelimb duty factor was higher than the mean hindlimb duty factor whilst moving at different speeds over ground (Maes *et al.*, 2008). This may represent differences associated with treadmill compared to overground locomotion which have already been highlighted in the literature (Gillette and Angle, 2008). At higher speeds, the duty factor of the hindlimb has been shown to be higher than that of the forelimb (Maes *et al.*, 2008), perhaps as a result of dogs powering their locomotion from the hips at faster speeds (Lee *et al.*, 1999; Usherwood and Wilson, 2005) and alterations in body posture (Walter and Carrier, 2009). This may be comparable to the power required to counteract the increased water resistance experienced in aquatic locomotion, hence providing a possible explanation for the increased duty factor seen in the hindlimb.

Stance and Swing Time

There were significant effects of water depth on both stance and swing time in addition to overall stride time. Swing time increased with increasing water depth as would be expected due to water resistance. Whilst there was a significant effect of water depth on the stance time of the forelimb and the hindlimb, significant differences were not identified between all depths as was the case with swing time and stride time. This suggests that the decrease in duty factor observed may be more attributable to increases in swing time and overall stride time than changes to the stance period. In terrestrial locomotion changes in duty factor

usually occur as a result of changes to stance time, rather than swing (Maes *et al.*, 2008). However, whether the increases in swing time and decreases in duty factor observed have implications for the peak ground reaction force the dog experiences is unclear due to the counteracting effect of buoyancy. When horses trot over poles, their swing time is necessarily increased in a similar fashion to the constraint of water on the swing arc in dogs. However, it has been demonstrated that trotting horses over poles does not increase the peak ground reaction force (Clayton *et al.*, 2015).

Stride Parameters

Stride length increased with water depth and stride frequency was observed to decrease. Although stride length has been found to decrease with increasing water depth in humans (Denning, 2010), equine studies have shown a similar trend to the significant differences observed in this study (Scott *et al.*, 2010). As water depth increases so does the effect of buoyancy (King *et al.*, 2013; Levine *et al.*, 2010; Owen, 2006; Prankel, 2008; Saunders, 2007) this could assist the dog in lifting the limb vertically allowing a longer flight arc of the limb and therefore decreasing stride frequency (Scott *et al.*, 2010). This could also be caused by dogs adapting their gait to enable more efficient movement through deeper water; increasing the height of the flight arc may also act to decrease the amount of resistance caused by the water whilst swinging the limb in the sagittal plane (Scott *et al.*, 2010).

Potential applications of these findings include using deeper water depths to promote a longer stride length and therefore increased speed in racing greyhounds or agility dogs (Hudson *et al.*, 2012), or for improving stride length postoperatively. The use of deeper water and therefore reduced stride frequencies whilst exercising patients with joint problems such as osteoarthritis may reduce the amount of mechanical wear on the joints. This could allow the dog to exercise and keep within a healthy weight whilst concurrently delaying the progression of osteoarthritis (Henrotin *et al.*, 2005). Depth is also important in the selection of protocols for chondrodystrophic breeds which may utilise unnatural head postures in deeper water (Prankel, 2008). In this study, whilst dogs were of mixed breed, they were of a fairly comparable conformation. Therefore, these data cannot be directly applied to the canine population as a whole and further work is required to investigate the effect of water depth on the kinematics of different breeds.

Hydrotherapy is currently an under-researched field and this study has highlighted a number of areas where further work is required to fully appreciate the role of canine hydrotherapy and its effect on the kinematics of dogs. Research into the appropriate number of acclimatization sessions to achieve a repeatable gait on the underwater treadmill would also be useful as this would provide a gold standard methodology for subsequent studies. In addition, clinical studies into the kinematics of dogs with musculoskeletal conditions such as osteoarthritis are needed to fully appreciate the effect of canine hydrotherapy on gait parameters in pathological animals.

Conclusion

Dogs walking on an UWT decreased their duty factor with increasing water depth. Significant changes in other stride parameters were also found, with stride length increasing and stride frequency decreasing with increasing depth. Small alterations in water depth can have a significant impact on how dogs move and as such water depth is an important variable that should be carefully considered in the design of canine hydrotherapy programs.

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Conflicts of interest: none

Figure Legends

Figure 1 - Schematic of the canine hydrotherapy treadmill and the different water depths. Illustration of the canine underwater treadmill (not to scale). Dashed lines approximate the water depths used; from lowest to highest (mid-tarsal, between the lateral malleolus and lateral epicondyle and between the lateral epicondyle and greater trochanter). Internal treadmill dimensions were 1.82m x 0.68m x 0.90m.

Figure 2 - Duty factor of all dogs at four different water depths. 1 = dry, 2 = mid-tarsal, 3 = between the lateral malleolus and the lateral epicondyle, 4 = between the lateral epicondyle and the greater trochanter. FL = forelimb, HL = hindlimb. Circles represent outliers.

Figure 3 – Stride length (m) of all dogs at four different water depths 1 = dry, 2 = mid-tarsal, 3 = between the lateral malleolus and the lateral epicondyle, 4 = between the lateral epicondyle and the greater trochanter.

Figure 4 – Stride Frequency (Hz) at four water depths. 1 = dry, 2 = mid tarsal, 3 = between the lateral malleolus and the lateral epicondyle and 4 = between lateral epicondyle and greater trochanter. Circles represent outliers.

Figure 5 - Stance and Swing Time (ms) at four water depths. 1 = dry, 2 = mid tarsal, 3 = between the lateral malleolus and the lateral epicondyle and 4 = between lateral epicondyle and greater trochanter. FL = forelimb, HL = hindlimb. Circles represent outliers.

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